

Observational Limits on Inverse Compton Processes in GRBs

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ABSTRACT

Inverse Compton (IC) scattering is one of two viable mechanisms that can produce the prompt non-thermal soft gamma-ray emission in Gamma-Ray Bursts. IC requires low energy seed photons and a population of relativistic electrons that upscatter them. The same electrons will upscatter the gamma-ray photons to even higher energies in the TeV range. Using the current upper limits on the prompt optical emission we show that under general conservative assumption the IC mechanism suffers from an “energy crisis”. Namely, IC will over-produce a very high energy component that would carry much more energy than the observed prompt gamma-rays, or alternatively it will require a low energy seed that is more energetic than the prompt γ -rays. Our analysis is general and it makes no assumptions on the specific mechanism that produces the relativistic electrons population.

Key words: Gamma Rays: bursts—ISM: jets and outflows—radiation mechanisms: nonthermal

1 INTRODUCTION

The mechanism that produces the prompt gamma-ray emission in Gamma Ray Burst (GRBs) is still uncertain. The non-thermal character of the spectrum points out towards Inverse Compton (IC) and Synchrotron as the two natural candidates. The latter become,

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somehow, the “standard” process but the former remained always a serious alternative (Shemi 1994; Shaviv & Dar 1995; Sari, Narayan & Piran 1996; Sari & Piran 1997; Waxman 1997; Ghisellini et al. 2000; Stern & Poutanen 2004; Kobayashi et al. 2007, and others). The observations of numerous bursts with low energy spectral slopes that are inconsistent with synchrotron (Cohen et al. 1997; Preece et al. 1998; Ghisellini et al. 2000; Preece et al. 2002) provided additional motivation to consider IC. Recently Kumar & McMahon (2008) have shown further inconsistency with the overall synchrotron model and suggested that Synchrotron Self-Compton (SSC) can resolve some of these problems.

The recent observations of a naked eye optical flash from GRB080319b (Racusin et al. 2008; Bloom et al. 2008; D’Elia et al. 2008) that coincided in time with the prompt γ -ray emission provided further motivation to consider IC as the source of the prompt γ -rays. Among the different models that appeared so far (Kumar & Panaitescu 2008; Fan & Piran 2008; Zou, Piran & Sari 2008; Yu, Wang & Dai 2008), several favor models in which the prompt γ -ray emission is IC of the optical flash and there have been suggestions that this is generic to many GRBs.

Motivated by these ideas we examine, here, the possibility that IC is the source of the prompt soft γ -ray emission in GRBs. This requires a soft component at the IR-UV range that serves as the seed for the IC process. The flux of these seed photons is constrained by observations (or upper limits) of the prompt optical emission. GRB 990123 (Akerlof et al. 1999) and GRB 080319B (Racusin et al. 2008) are rare exceptions with very strong optical emission, ~ 9 and ~ 5.3 mag respectively. However most bursts are much dimmer optically with observations or upper limits around 14 mag (Yost et al. 2007). This should be compared with fluxes of mJy in soft gamma rays for a modest burst. What is important, in this work is the flux ratio F_γ/F_{opt} which is typically larger than 0.1 during the peak soft gamma emission (Yost et al. 2007).

The basic problem of the IC model can be explained simply. If the low energy seed emission is in the optical, while the observed soft γ -ray spectrum is the first IC component, then second IC scatterings would create a TeV component. Upper limits or observations of the prompt optical signal show that the Y parameter, i.e. the ratio between the energy in the first IC component to that in the low energy seed photons is very large, typically greater than thousands. Theory would then show that the second IC component in the TeV range would carry an even larger amount of energy, again by a factor of $Y \gg 1$, producing an “energy crisis” for this model, and possibly violating upper limits from EGRET (Energetic

Gamma-Ray Experiment Telescope)¹ (Gonzalez & Sanchez 2005; Ando, Nakar & Sari 2008). This problem is generic and it does not depend on the specific details of the overall model.

The above analysis is oversimplified and two factors may alleviate the energy catastrophe. First, the frequency of the seed photons may differ from that where upper limits exist, allowing larger seed flux and reducing the lower limits on Y . Second, the Klein-Nishina (KN) suppression, which does not affect the first scattering, may affect the second, resulting in a lower Y parameter for the second scattering than the first one. In this article, we explore the parameter space to see whether there exist a regime where a combination of these two factors allows for less energy in the second IC component (Typically in the TeV range) than in the γ -rays. We find that possible solutions are limited to a very small region in the parameters space in which the seed photons are in the IR, the bulk Lorentz factor is very low (≤ 200) and the electrons' Lorentz factor is very large (≥ 2000). However, this solution implies a healthy emission in the IR, while self absorption limits it. Therefore, when taking self-absorption into account, this solution is ruled out as well. A second possible solution exists if the seed photons are in the UV. This solution requires a very low electrons' Lorentz factor ≤ 100 , and a seed photon flux that carries comparable energy to the observed prompt γ -rays. Furthermore, prompt X-ray observations limit the high energy tail of the UV component and practically rule out this model.

We take the Lorentz factor of the electrons and the bulk Lorentz factor as free parameters and we estimate what is the second IC fluence (at TeV or multi GeV) given the observed prompt gamma-ray flux and the limits on the prompt optical band. Most of our analysis is insensitive to the size of the source, which appears only in the final section when we estimate the self absorption flux. In our numerical examples we use very conservative parameters. For example we use R magnitude of 11.2 as an upper limit on the optical flux, while many limits are much stronger and the γ -ray flux we take, $10^{-26} \text{erg cm}^{-2} \text{s}^{-1} \text{Hz}^{-1}$, is quite modest. Similarly we use conservative rather than “canonical” values for the spectral slopes.

2 BASIC EQUATIONS

Consider electrons that move with a bulk Lorentz factor $\Gamma \gg 1$ while in the bulk (or fluid) rest frame they have a typical Lorentz factor $\gamma_e \gg 1$ in a random direction. We examine IC scattering of seed photons with a peak frequency ν_{seed} and a peak flux F_{seed} (both measured

¹ Deeper upper limits on a wider energy range, may soon come up from Fermi, making our argument stronger.

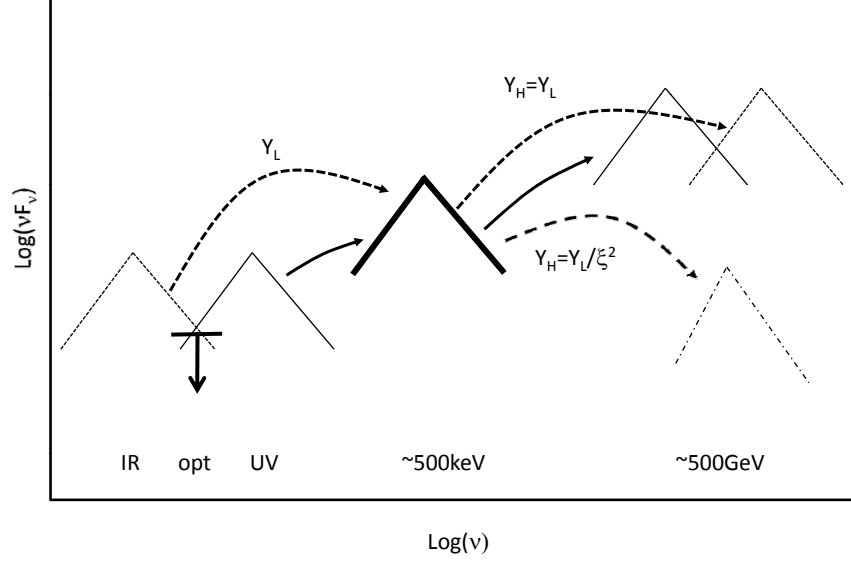


Figure 1. A schematic description of the IC process. Low energy photons at the IR (marked in dotted lines), optical or UV (marked in solid thin lines) are IC scattered to produce the observed soft gamma ray emission (marked in bold lines). A second IC scattering brings the soft gamma photons to the TeV region. If the initial seed photons are softer the higher energy component is harder. If the initial seed is in the IR then the second IC process might be in the KN regime, in which case this component is suppressed (dashed-dotted line). The seed low energy emission is constraint by upper limits on the optical prompt observations (bold solid arrow).

at the observer's rest frame). We assume that the seed photons are roughly isotropic in the fluid's frame. This would be the case if the seed photons are produced by synchrotron radiation in the bulk, or any other mechanism local to the moving fluid. We will consider External IC, in which the seed photons are produced by an external source elsewhere. For simplicity we assume that all the photons have the same energy and all the electrons have the same Lorentz factor. The energy and flux of the scattered photons are:

$$\nu_{IC} = \nu_{seed} \gamma_e^2 \min(1, \xi^{-1}) \quad (1)$$

and

$$\nu_{IC} F_{IC} = \nu_{seed} F_{seed} Y \min(1, \xi^{-2}) \quad (2)$$

where $Y \equiv \tau \gamma_e^2$ and τ are the Compton parameter and the optical depth in the Thomson scattering regime. Note that the unknown optical depth, τ , is introduced here in the definition of Y but it is not used elsewhere in the paper. Our analysis is independent of this unknown factor. The factor, ξ corresponds to the correction that arises if the scattering is

in the KN region:

$$\xi \equiv \frac{(\gamma_e/\Gamma)h\nu_{\text{seed}}}{m_e c^2} > 1. \quad (3)$$

The expression given in Eq. 3 is approximate. Again this approximation is sufficient for our purpose.

We consider now the possibility that the prompt gamma-rays arise due to IC scattering of a lower energy component. We use now the observed gamma-ray flux, F_γ , and its peak energy, ν_γ and the upper limits (or detections) of prompt optical emission, F_{opt} at ν_{opt} to set limits on the IC process.

The peak flux of the low energy component, F_L , is at ν_L which is not necessarily at the observed frequency ν_{opt} . Given an upper limit on the prompt optical flux, F_{opt} at ν_{opt} (or on the flux at any other frequency), we can set a limit on F_L if the optical frequency is in the same spectral region as ν_L , the peak frequency of the lower spectral component of slope α :

$$F_L \leq (\nu_L/\nu_{\text{opt}})^\alpha F_{\text{opt}}. \quad (4)$$

The equality here and elsewhere holds when F_{opt} corresponds to a detection and an inequality corresponds to an upper limit. There are two possibilities, either $\nu_L > \nu_{\text{opt}}$ which we call the “UV solution” or $\nu_L < \nu_{\text{opt}}$ which we call the “IR solution”. Since by definition, the seed photon energy peaks at ν_L , we must have $\alpha > -1$ in the UV solution and $\alpha < -1$ in the IR solution. Moreover, since the spectrum around ν_L is up-scattered to create the familiar Band spectrum (Band et al. 1993) around ν_γ , we can expect $\alpha \approx -1.25$ for the IR solution and $\alpha \approx 0$ for the UV solution.

As the first IC scattering results in soft γ -rays, it is clearly away from the KN regime and we obtain, using Eqs. (1,2,4) a limit on the Compton parameter Y_L , in the first Compton scattering:

$$Y_L \geq \left(\frac{\nu_\gamma F_\gamma}{\nu_{\text{opt}} F_{\text{opt}}} \right) \left(\frac{\nu_L}{\nu_{\text{opt}}} \right)^{-(1+\alpha)}. \quad (5)$$

Using this limit we turn now to the second order IC component. This process will produce photons in the GeV-TeV range. As the scattered photon is energetic, it might be in the KN regime and we have:

$$\nu_H = \nu_\gamma \left(\frac{\nu_\gamma}{\nu_{\text{opt}}} \right) \left(\frac{\nu_{\text{opt}}}{\nu_L} \right) \min(1, \xi^{-1}) \quad (6)$$

and

$$Y_H \geq \left(\frac{\nu_\gamma F_\gamma}{\nu_{\text{opt}} F_{\text{opt}}} \right) \left(\frac{\nu_L}{\nu_{\text{opt}}} \right)^{-(1+\alpha)} \min(1, \xi^{-2}). \quad (7)$$

Y_H is the ratio of energy emitted in the high energy (TeV) band and in lower energy gamma-rays (see Fig. 1).

As a conservative numerical example we will use the following typical parameters: $F_\gamma = 10^{-26} \text{ergs cm}^{-2} \text{s}^{-1} \text{Hz}^{-1}$, $F_{opt} \leq 10^{-24} \text{ergs cm}^{-2} \text{s}^{-1} \text{Hz}^{-1}$, leading to a ratio of $F_\gamma/F_{opt} \geq 0.01$. This optical flux corresponds to R magnitude 11.2, which is a very conservative upper limit to the prompt optical emission of most GRBs while the prompt gamma-ray flux is moderate. We use $\nu_{opt} = 8 \cdot 10^{14} \text{Hz}$ and $h\nu_\gamma = 500 \text{keV}$ [both energies are larger by a factor of $(1+z) \approx 2$ than the observed frequencies, R band and 250keV]. Thus $\nu_\gamma F_\gamma / (\nu_{opt} F_{opt}) \geq 1500$. We will use $\Gamma = 300$ and $\gamma_e \equiv (\nu_\gamma / \nu_{opt})^{1/2} \simeq 400$ for the canonical values of ν_γ and ν_{opt} . We find:

$$h\nu_H = 0.08 \text{TeV} \left(\frac{h\nu_\gamma}{500 \text{keV}} \right) \left(\frac{\gamma_e}{400} \right)^2 \min \left[1, \frac{\Gamma m_e c^2}{\gamma_e h\nu_\gamma} \right] \quad (8)$$

and

$$Y_H \geq 1500 \left(\frac{F_\gamma}{10^{-26}} \frac{10^{-24}}{F_{opt}} \right) \left(\frac{h\nu_\gamma}{500 \text{keV}} \frac{8 \cdot 10^{14} \text{Hz}}{\nu_{opt}} \right) \left(\frac{\nu_L}{\nu_{opt}} \right)^{-(1+\alpha)} \min \left[1, \left(\frac{\Gamma m_e c^2}{\gamma_e h\nu_\gamma} \right)^2 \right] \quad (9)$$

The essence of the IC problem is the very large value of Y_H , which arises from the fact that the energy released in prompt gamma-rays is at least a factor of 1500 larger than the energy released in prompt optical emission (see Eq. 5). The large values of Y_H implies that the energy emitted in the TeV range exceeds the observed soft γ -rays by several orders of magnitude.

Fig. 2 depicts Y_H as a function of ν_L for different values of Γ and for different spectral indices. Y_H peaks when $\nu_L = \nu_{opt}$. This is expected as in this case the observed limits on the lower energy flux are strongest. If ν_L increases or decreases more energy can be “hidden” in the lower energy component and the corresponding Y_L and Y_H will be smaller. Because of a similar reason Y_H decreases when $|\alpha + 1|$ increases.

We find two possible regimes for IC solutions that are not over producing a high energy (TeV) component. The UV solution requires $\nu_L > 10\nu_{opt}$ and $\alpha \geq 1$. The electrons’ Lorentz factor in the UV solution satisfies $\gamma_e < 100$. The second Compton scattering is not in the KN regime since $\Gamma > 100$ and correspondingly ξ is small. Since KN suppression is negligible $Y_L \approx Y_H$ and the total energy, given by $(1/Y_L + 1 + Y_H)E_\gamma$, is at least $3E_\gamma$. UV solutions with $Y_L = Y_H < 1$ are therefore also wasteful as they require a large (E_γ/Y_L) low energy component. A second problem arises, for this solution, with the spectral shape. The observed low energy spectral index (in the X-ray band) is typically close to zero, while this solution requires a steeply rising flux from ν_{opt} to ν_L . Note that in Fig. 2 we show conservatively

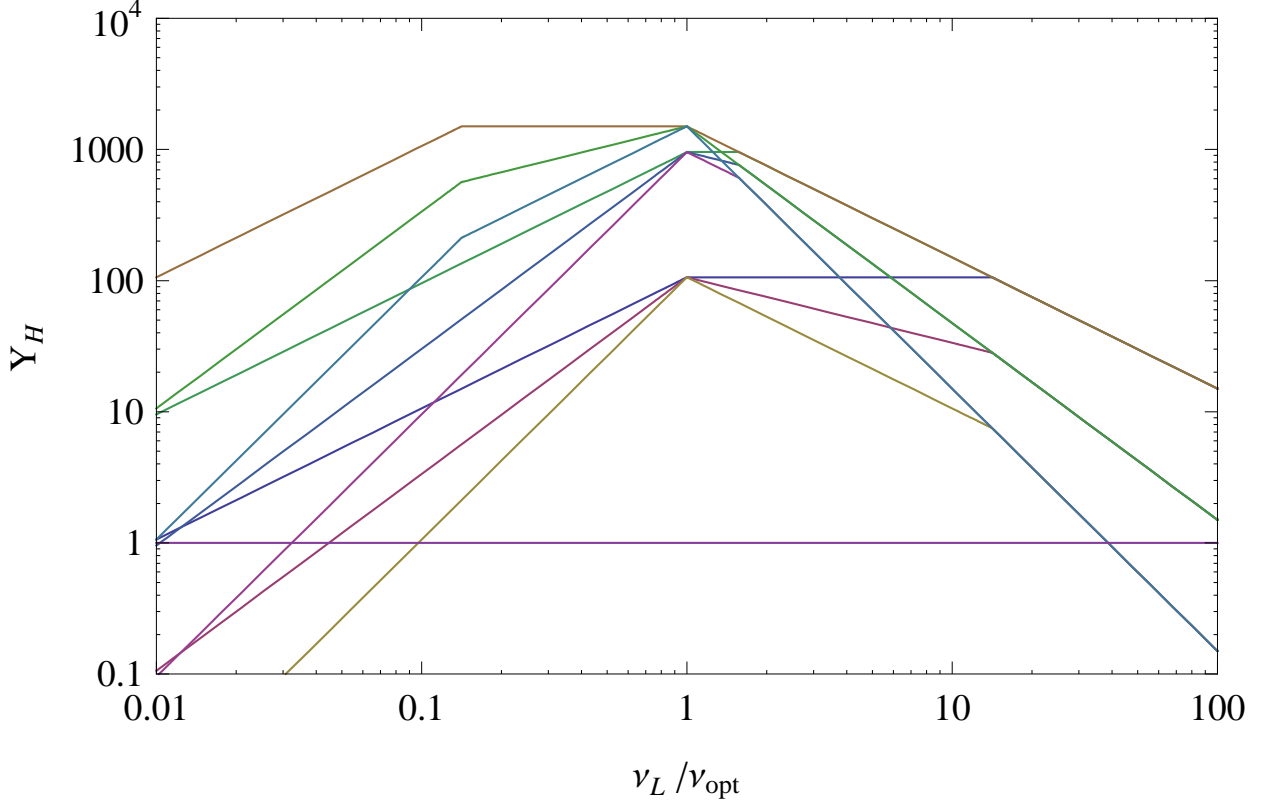


Figure 2. Y_H as a function of ν_L/ν_{opt} for $\Gamma = 1000, 300, 100$ (from top to bottom) and $\alpha = 0, 0.5, 1$ (from top to bottom) for $\nu_L > \nu_{opt}$ and $\alpha = -1, -1.5, -2$ for $\nu_L < \nu_{opt}$. Parameters used in this figure are: $F_\gamma/F_{opt} = 0.01$, $\nu_{opt} = 8 \cdot 10^{14}$ Hz and $h\nu_\gamma = 500$ keV. The breaks in the lines appear at $\nu_L = \nu_{opt}$ when we change from negative to positive α and at the frequency, that depends on Γ , where the KN correction begins.

curves for $\alpha = 0, 0.5, 1$ even though the "canonical" value is 0. Moreover, unless there is a pair loading (that is if there is one electron per proton), then the low γ_e required for the UV solution implies that the protons carry significantly more energy than the electrons by at least a factor of $m_p/\gamma_e m_e$. Thus this solution is a very inefficient.

The analysis above is based on the optical limits but for the modest values of γ_e needed for the UV solution, ν_L , the peak flux frequency of the seed photons becomes large (Eq. 1) and F_L is now limited by prompt soft X-ray observations in addition to the optical limits. For the discussion below, we use α_1 and α_2 as the low energy and high energy spectral indices, respectively. As stated before, the canonical values are $\alpha_1 = 0$ and $\alpha_2 = -1.25$ (Band et al. 1993)². One can estimate the X-ray flux at $\nu_x = 20$ keV directly from the observations at this energy or using the flux at $\nu_\gamma \approx 500$ keV and the low energy spectral slope α_1 . Recalling that the IC does not change the spectral slope, we use the same indices

² Since we consider flux rather than photon counts the indices are shifted by 1 relative to Band et al. (1993).

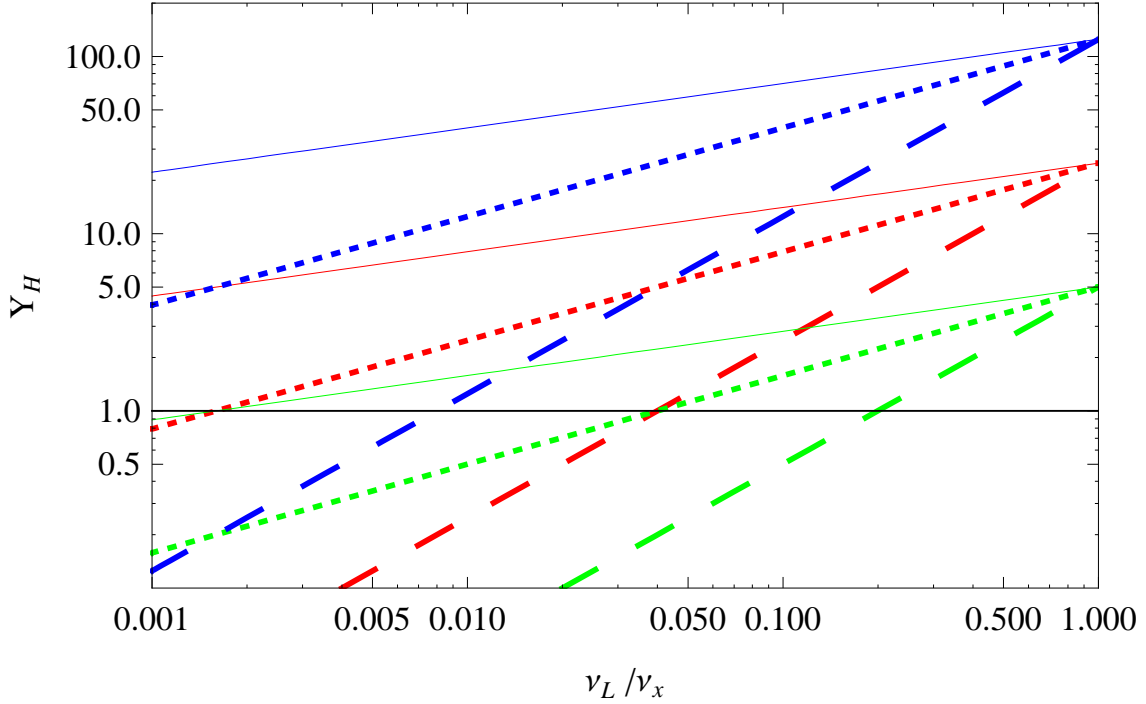


Figure 3. Y_H as a function of ν_L/ν_x for $\alpha_1 = -0.5, 0, 0.5$ (blue, red and green) and $\alpha_2 = -1.25, -1.5, -2$ (solid, dotted and dashed) for $h\nu_x = 20\text{keV}$ and $h\nu_\gamma = 500\text{keV}$. The corresponding γ_e range is from 158 at $\nu_L = 0.001\nu_x$ to 5 at $\nu_L = \nu_x$.

both around ν_γ and around ν_L . Therefore:

$$F_L < (\nu_L/\nu_x)^{\alpha_2} (\nu_x/\nu_\gamma)^{\alpha_1} F_\gamma. \quad (10)$$

Using Eq. 2 we obtain:

$$Y > \frac{\nu_\gamma^{\alpha_1+1} \nu_x^{\alpha_2-\alpha_1}}{\nu_L^{\alpha_2+1}} = (\nu_\gamma/\nu_x)^{\alpha_1-\alpha_2} \gamma_e^{2(\alpha_2+1)}. \quad (11)$$

Since the UV solution is not in the KN regime we have $Y = Y_L = Y_H$. If we take the typical spectral indices below and above ν_γ to be $\alpha_1 = 0$ and $\alpha_2 = -1.25$ respectively (Band et al. 1993), and we impose the condition $Y \cong 1$ (where the total energy required is minimized to $3E_\gamma$), we find that $\gamma_e > 3000$ or $\nu_L < \nu_{opt}$ - thus the whole UV regime is ruled out. This condition depends strongly on the spectral indices: α_1 and α_2 . Clearly if α_2 is smaller (a steeper drop on the high energy side) ν_L can be larger and Y is smaller³. The limits are depicted in Fig. 3 for several values of the spectral indices. One can see that the available X-ray data rules out the UV solution for most of the phase space.

The IR solution holds for $\nu_L < 0.1\nu_{opt} = 8 \cdot 10^{13}\text{Hz}$ and $\alpha \leq -1.5$. It requires a large electron's Lorentz factor $\gamma_e \geq 1000$ and a relatively low bulk Lorentz factor $\Gamma < 300$. The solution is deep in the KN regime and the KN suppression is very significant. It allows for

³ It is interesting to note that $|\alpha_2|$ is large for GRB 080319b, which might be an IC burst with a UV solution.

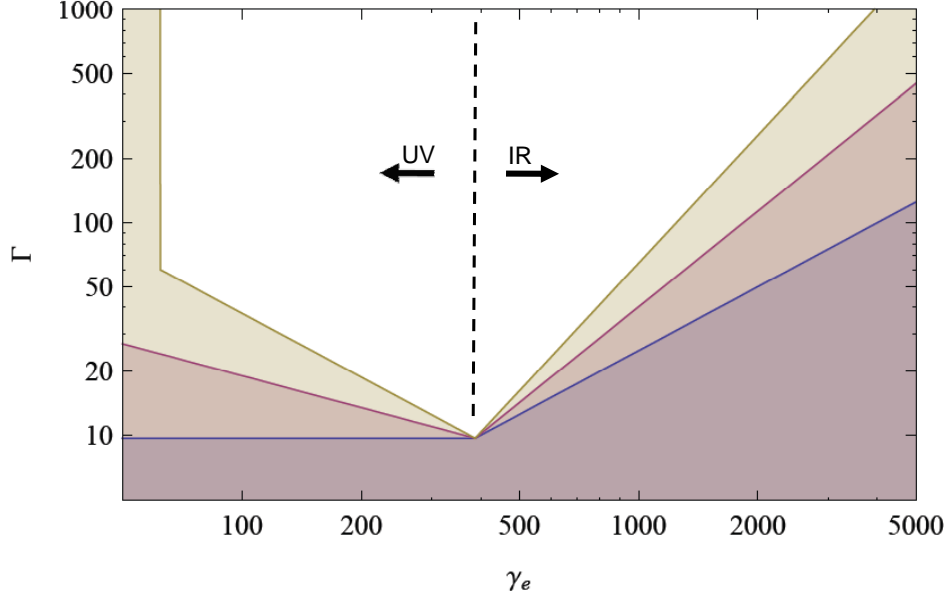


Figure 4. The allowed (colored) phase space in which $Y_H \leq 1$. For three spectral indexes $\alpha = 0, 0.5, 1$ (from bottom to top) for $\nu_L > \nu_{opt}$ and $\alpha = -1, -1.5, -2$ for $\nu_L < \nu_{opt}$ (from bottom to top). Parameters used are: $F_\gamma/F_{opt} = 0.01$, $\nu_{opt} = 8 \cdot 10^{14}$ Hz and $h\nu_\gamma = 500$ keV. The γ_e axis corresponds to values of ν_L ranging from $15\nu_{opt} = 4.8 \cdot 10^{16}$ Hz = 0.2 keV for $\gamma_e = 50$ to $0.006\nu_{opt} = 4.8 \cdot 10^{12}$ Hz for $\gamma_e = 5000$.

a large amplification between the IR and the soft γ -rays and no amplification between the low energy gamma and the TeV emission. A solution is possible in a small region of the parameter space if the high energy spectrum is steep ($\alpha \leq -1.5$) - this increases the allowed flux at ν_L . Such a spectrum above the peak frequency, though steeper than the canonical $\alpha = -1.25$, is not rare in the observations of prompt γ -ray bursts.

To demonstrate the severity of the constraint we plot (Fig. 4) the “allowed region” in the (γ_e, Γ) phase space for which $Y_H < 1$. It is remarkable to note that the expected parameter region for internal shocks $\gamma_e \approx 500$, $\Gamma \approx 300$ is deep inside the ruled out region. The parameter expected for external shocks $\gamma_e \approx 50,000$ and $\Gamma \approx 300$ are allowed with seed photon wavelength in the cm range. However, as we show in §4, self absorption limits the amount of energy in such low frequency seed photons, ruling out this solution. For low values of γ_e the whole Γ range is seemingly allowed. However, this only happens at $\gamma_e < 62, 34, 10$ for $\alpha = 1, 0.5, 0$ respectively, and therefore conflicts with the soft X-ray observations.

3 PAIR AVALANCHE

In cases when $Y_H > 1$ most of the electrons energy is emitted as very high energy (TeV) gamma-rays. When the scattering is in the KN regime, that is if Eq. 3 holds, the scattered photon, that has an energy of almost $\gamma_e m_e c^2$ (in the fluid's rest frame) and can therefore produce a pair when it encounters a typical low energy γ -ray photon with energy $h\nu_\gamma/\Gamma$ (in this frame). More specifically, for a head on collision between a photon with energy $h\nu_\gamma = \xi\Gamma m_e c^2/\gamma_e$ and an electron with a Lorentz factor γ_e , the energies of the electron and the photon after the collision are:

$$h\nu \approx \frac{4\xi}{1+4\xi} \Gamma \gamma_e m_e c^2, \quad (12)$$

and

$$\hat{\gamma} \approx \frac{1}{1+4\xi} \gamma_e \quad (13)$$

The resulting photon has now enough energy to collide with a photon with energy $h\nu_\gamma$ and produce two electrons with a Lorentz factor:

$$\tilde{\gamma} \approx \frac{4\xi}{1+4\xi} \frac{\gamma_e}{2} \approx \frac{\gamma_e}{2}. \quad (14)$$

As the optical depth for pair creation is huge all the scattered photons will create pairs with typical energy of $\gamma_e m_e c^2/2$. As a result we will have colder electrons and positrons with a ratio 2:1 in higher ($\gamma_e/2$) and lower ($\gamma_e/4\xi$) energies. These colder electrons and pairs will Inverse Compton scatter more photons and will produce a second generation of cooler pairs with $\gamma_e/4$. The process will continue until pair creation will stop. This will happen when $\tilde{\gamma} h\nu_\gamma/\Gamma \approx m_e c^2$. This situation was considered numerically by Coppi (1992); Stern et al. (1995); Pe'er & Waxman (2005), and most recently Vurm & Poutanen (2008).

If the physical conditions, like magnetic field and total number of particles are fixed ν_L , ν_γ and ν_H as well as the corresponding fluxes will vary as a result of the changing electron energy distribution due to the created pairs. These variations will be very significant because of the strong dependence (2nd and 4th powers) of the first two on γ_e . The dynamical evolution of such a system is interesting by itself. However, we are interested, here, in the final steady state in which ν_γ and F_γ are fixed as the observed quantities. In this case we can search for the physical parameters that exists in such a steady state. We can express Γ in terms of γ_e and ν_γ using the pair creation threshold criteria (Eq. 3) and we can express ν_L in terms of ν_γ and γ_e (using Eq. 1). Given these expressions we can estimate the steady state Y_H as a function of γ_e .

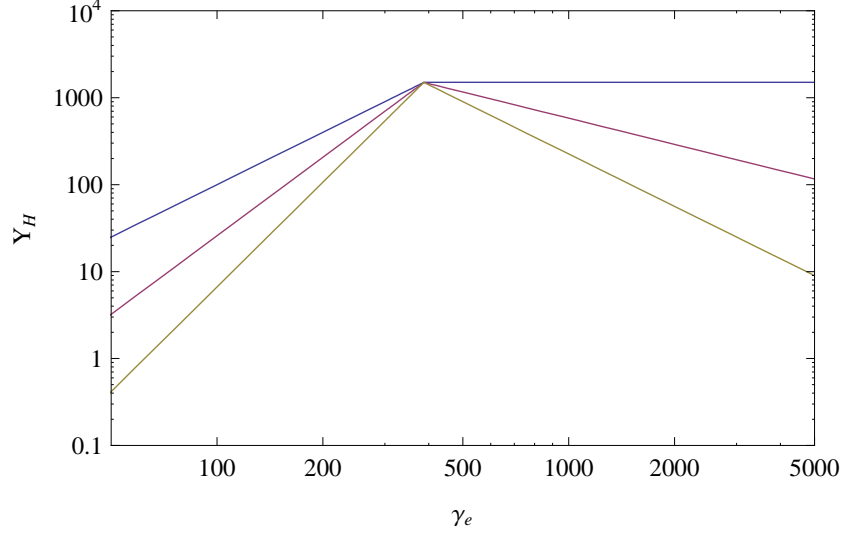


Figure 5. The steady state Y_H as a function of γ_e for a situation in which pair avalanche leads to $\gamma_e = m_e c^2 \Gamma / h \nu_\gamma$. Shown are curves for three different values of $\alpha = 0, 0.5, 1$ (from top to bottom) for $\nu_L > \nu_{opt}$ and $\alpha = -1, -1.5, -2$ for $\nu_L < \nu_{opt}$. The Parameters used are: $F_\gamma / F_{opt} = 0.01$, $\nu_{opt} = 8 \cdot 10^{14} \text{ Hz}$ and $h \nu_\gamma = 500 \text{ keV}$. The γ_e axis corresponds to values of ν_L ranging from $15\nu_{opt} = 4.8 \cdot 10^{16} \text{ Hz} = 0.2 \text{ keV}$ for $\gamma_e = 50$ to $0.006\nu_{opt} = 4.8 \cdot 10^{12} \text{ Hz}$ for $\gamma_e = 5000$.

Fig. 5 depicts the resulting Y_H values as a function of γ_e for different values of α . The UV solution for $\nu_L > 10\nu_{opt}$ and with rather low values of γ_e and Γ is possible. However this solutions suffers from the problems discussed earlier. It seems that if we impose the pair creation threshold conditions the IR solution is ruled out with very high Y_H values (for any reasonable α). However, as discussed earlier, there is a region in the parameter space for the IR solution for which $Y_H \leq 1$. In this case only a small fraction of the energy goes into the high energy photons and it is possible (depending on time scales) that most of the electrons cool down rapidly before pair avalanche arises.

4 THE SEED PHOTONS AND SELF-ABSORPTION

A natural source of the seed photons is synchrotron emission by the same electrons that produce the IC emission. Assuming that this source is indeed synchrotron we can proceed and estimate the strength of the magnetic field and the size of the emitting region. We can then check if these values are reasonable within given GRB models. However, we choose a more general approach and ask whether the large seed flux needed is limited by self absorption.

Self absorption limits the flux at ν_L to be below the black body flux, F_{sa} , for a local

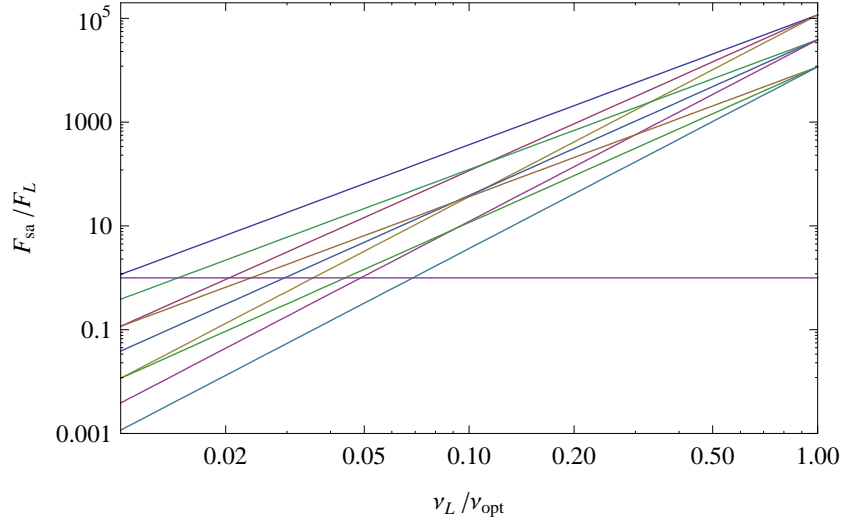


Figure 6. The ratio of the self absorbed flux F_{sa} to the needed seed flux as function of ν_L/ν_{opt} for three values of $\Gamma = 100, 300, 1000$ (from top to bottom) and three different values of α : $\alpha = -1, -1.5, -2$ (from top to bottom) for $\nu_L < \nu_{opt}$. Parameters used in this figure are: $F_\gamma/F_{opt} = 0.01$, $\nu_{opt} = 8 \cdot 10^{14}$ Hz and $h\nu_\gamma = 500$ keV.

temperature $kT \approx \Gamma \gamma_e m_e c^2$:

$$F_{sa}(\nu_L) = \frac{2\nu_L^2}{c^2} \gamma_e m_e c^2 \frac{R^2}{4\Gamma d_L^2} \quad (15)$$

$$\approx 1.3 \cdot 10^{-20} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ Hz}^{-1} \frac{(R/10^{17} \text{ cm})^2}{d_L^2(z=1)} \frac{(\nu_\gamma/500)^2}{(\gamma_e/400)^3 (\Gamma/300)},$$

where R is the radius of the source and $d_L(z=1)$ is the luminosity distance for $z=1$. In the following examples we use conservatively $R = 10^{17}$ cm as the emission radius of the prompt emission.

Fig. 6 depicts a comparison of this limiting flux, F_{sa} with the needed flux $F_L = F_\gamma \gamma_e^2 / Y_L$. For $\nu_L > 0.1\nu_{opt}$, $F_{sa} < F_L$. This implies that the electrons that produce the IC emission cannot produce the lower energy seed photons. The ratio F_{sa}/F_L decreases with increasing Γ . It also decreases when $|\alpha|$ increases. So in most of the region where $Y_H < 1$ (see fig. 2) the seed flux is insufficient!

The combined limits on the (Γ, γ_e) parameter space from self absorption with $Y_H = 1$ are shown in fig. 7. Only an extremely small region around $\gamma_e \approx 1800$ (corresponding to $\nu_L = 3.7 \cdot 10^{13}$ Hz) and $\Gamma \approx 120$ is allowed. This used a conservative over estimate for the emission radius $R = 10^{17}$ cm. If we use the variability time scale $\delta t < 1$ sec, with $R \sim \Gamma^2 c \delta t$ and the low values of Γ obtained, R will be much smaller, invalidating even this solution. The self absorption limit rules out also the region in the parameter space that corresponds to external shocks. This solution requires a very low seed frequency which would have implied a very small self-absorption limit.

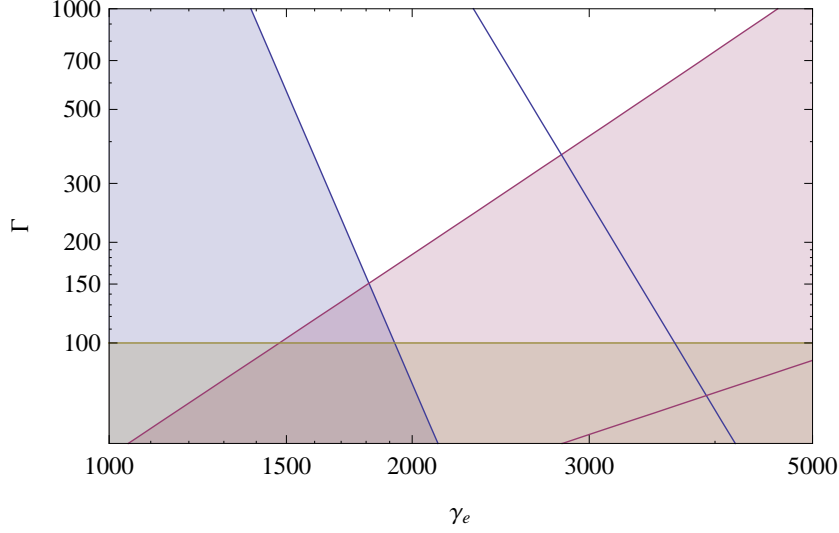


Figure 7. Allowed region for the IR solution in the (Γ, γ_e) parameter space. The limit on the left (decreasing curve) corresponds to the condition $F_{sa} \geq F_L$. The limit on the right (increasing curve) corresponds to $Y_H = 1$. Also marked is $\Gamma = 100$, which is considered as a minimal value for the bulk Lorentz factor to resolve the compactness problem (Lithwick & Sari 2001). The limits are shown for $\alpha = -2$. (On the right side around $\gamma_e = 4000$ shown are the corresponding curves for $\alpha = -1$). The γ_e range from 1000 to 5000 corresponds to $\nu_L = 1.2 \cdot 10^{14}$ Hz to $\nu_L = 4.8 \cdot 10^{12}$ Hz. Parameters used in this figure are: $F_\gamma/F_{opt} = 0.01$, $\nu_{opt} = 8 \cdot 10^{14}$ Hz and $h\nu_\gamma = 500$ keV. For $\alpha = -2$ an extremely small region around $\gamma_e \approx 1800$ (corresponding to $\nu_L = 3.7 \cdot 10^{13}$ Hz) and $\Gamma \approx 120$ is allowed.

5 CONCLUSIONS

For a typical GRB, IC has to amplify the total energy of a low energy seed photon flux by a factor of ≈ 1000 to produce the observed prompt gamma-ray flux. The same relativistic electrons will, however, continue and upscatter the gamma-ray flux to very high energies in the TeV range. In many cases this second generation IC will be in the Klein-Nishina regime (that is the photon's energy will be larger than the electrons rest mass, in the electron's rest frame). This will suppress somewhat the efficiency of conversion of gamma-rays to very high energy gamma-rays, however it won't stop it altogether.

Our analysis focused on the case that the low energy seed photons are produced within the moving region that includes the IC scattering relativistic electrons. Such will be the case, for example, in Synchrotron self-Compton. Related considerations, that will be published elsewhere, apply when the seed photons are external and constrain IC processes in this case as well. The analysis is also limited to the important implicit assumption that the emitting region is homogenous. It is possible that very strong inhomogeneities could change this picture.

We have shown that, under quite general conservative assumptions, if IC produces the prompt MeV photons, then a second scattering will over produce a very high (GeV-TeV) prompt component that will carry significantly more energy than the prompt gamma-rays

themselves. On the theoretical front such a component will cause an “energy crisis” for most current progenitor models. From an observational point of view, this component is possibly already ruled out by EGRET upper limits (Gonzalez & Sanchez 2005; Ando, Nakar & Sari 2008). Fermi should very soon put much stronger limit to (or verify) this possibility. For example, a burst with isotropic energy $E_{\gamma,iso} = 10^{53}$ erg, locating at $z = 1$, would produce $\sim 100Y_H(E_H/10\text{GeV})$ photons detected by Fermi.

One may not over produce a high energy component if the seed photons are in the UV regime. However, in this case, the needed seed photon energy should be equal or larger than the observed prompt gamma-ray energy. Downwards extrapolation of the X-ray observations put strong limits on this solution and probably rule it out as well. Moreover this UV solution requires pair loading to be efficient.

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